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ROCKFALLS, LANDSLIDES, AND CREEP IN THE CANARIES

BY

HANS HAUSEN

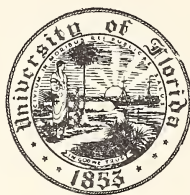


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ABSTRACT

In connection with a study recently begun on the geomorphological development of the Canary Islands, the author has investigated gravitational adjustments due to non-volcanic forces operating in these islands of volcanic origin. The most prominent exogenic process is river erosion, followed by marine abrasion. Ground movements result from undercutting, water saturation in the volcanic beds and disturbances caused by earthquakes in the islands' generally brittle geological structure. Many important geomorphological features can be interpreted as the result of these ground adjustments, including the great Caldera de las Cañadas encircling Pico de Teide in Tenerife, formerly regarded as a collapse caldera of volcanic origin. Likewise, other prominent embayments can be explained by assuming large-scale landslides. Most of these occurrences belong to the Quaternary period, to a time when rainfall was greater and earthquakes associated with the now fading volcanism were more frequent.

INTRODUCTION

The Canary Islands have already been investigated geologically on many occasions (Bibl. Hausen 1956—1971). Most attention has been paid to the volcanic formations that dominate in their geologic structure. The exogenic geologic features have, however, with one exception been comparatively little dealt with (Klug, 1968).

This time the author wishes to take up a problem referring to the exogenic events in Canarian geologic evolution that seems to be of considerable importance, viz. the landslides, rockfalls and creep of rock waste that have happened in the course of Tertiary, Quaternary and recent times. It must, however, be declared that more penetrating investigations have not been carried out. My purpose is only to call attention to these phenomena.

Slumpings and landslides have happened in many lands in very different environments, and many such events have been studied, chiefly

from technical points of view. The literature dealing with these phenomena is ample. In most cases the studies refer to very young and weak sediments in connection with road and building constructions. A treatise discussing all possible variants in gravitational adjustments within young sedimentary ground is O. Zaruba's and V. Mencl's »Landslides» (1969). As far as volcanic lands are concerned such studies have scarcely been carried out.

The gravitational adjustments of the ground in a volcanic environment like that of the Canary Islands offer special problems. Because the study is not limited to more recent materials, but comprises also grounds of more remote periods, the problem is complicated, since volcanic eruptions have from time to time interfered with exogenic adjustments.

For that reason the superficial gravitational adjustments are not always apparent, and in a technical sense they are mostly of minor importance. Nevertheless their role seems to be great in the morphology of the islands.

CAUSES OF GRAVITATIONAL ADJUSTMENTS IN THE CANARIES

We have at first to consider the degrees of stability of the Canary islands as far as their resistance to the destructive powers of the exogenic agencies is concerned.

The Canary Islands are lofty volcanic edifices rising from a relatively deep sea — they all lie within the African continental slope. Hence the westernmost islands have the deepest reaching submarine socles. Most of the islands are in fact accumulations of volcanic material of spectacular height from the sea floor. Only the easternmost islands are not so high.

The geologic structure of the Canaries is of a very complicated nature with great variations in hardness and coherence among the different materials. In the main every one of the islands shows a succession of lava and tuff sheets more or less gently inclined towards the coast, where they end in steep shore cliffs.

It is evident that most of the islands are in the main young accumulations of volcanic material which have grown relatively briskly from the ocean floor and attained considerable heights above sea level. No wonder that they are vigorously attacked by the waves from all sides, chiefly from the north, so that the amount of rock destruction appears in huge cliffs. The waste derived from this process is dragged to the sea and deposited off shore as taluses or shelves.

Not only the waves have performed destructive work. The islands are standing in the stream of the northeasterly trade wind that brings moisture to the slopes and causes fog and rain. In this way the windward sides are condensers of humidity, and weathering and river erosion are the result. There are also many kinds of rock falls, landslides and creep to be considered.

It is of course difficult to treat the last named gravitational adjustments without considering the full effect of erosion by running water and marine abrasion. These factors have in the course of time created a broken relief typical of the Canary Islands. And this relief has given many bordering land areas instability, where sooner or later adjustments of some kind take over. In most cases it is a question of rock falls or minor slumpings, but under favourable conditions greater landslides can be released.

One cannot generalize conditions within the archipelago too much, since every one of the islands has had its special line of development or geologic history. If we think of erosion there are some curious contrasts: Hierro is nearly devoid of erosion valleys or barrancos, whereas the near-lying Gomera is intensely cut by a radiating system of these furrows. In the easternmost islands erosion has so progressed that the relief has been converted into a *Mittelgebirge*; where generally few sharp surface forms have been left.

It is not only the abrupt changes in altitude that create instability. An important role must be attributed to the soaking ground water that passes all the way across the island structure down to the level of the sea (where it accumulates as the basal ground water body). But all the water does not reach this body. A great deal of it is arrested in permeable layers within the volcanic structure like tuffs and agglomerates, especially where they are underlain by impermeable sheets of lava. In these water-enriched zones a weakening is produced and creep can be the result, because the layers have a certain grade to the

sea. Also slippings may result from time to time, and in special cases also great momentaneous landslides.

Such a weakening of the structure by infiltration of ground water was of course more common in times of abundant rains, as in the pluvials of the Quaternary period. The triggering effect may in many cases have been earthquakes accompanying volcanic outbursts, and those were formerly much more common than now. We may therefore suppose that landslides were formerly much more frequent phenomena in the Canaries than at present.

EXOGENIC GRAVITATIONAL ADJUSTMENTS IN THE ISLANDS

It seems most convenient to scrutinize the islands as they follow in order from west to east — from Hierro to Lanzarote, a distance of about 500 km. I have added to the text some small topographic maps of some of the islands. The islands must be considered one by one because they are different in many respects and are also of somewhat different ages. Also the climatic conditions are not uniform, there is a marked decrease in humidity from west to east, although the climatic conditions of the present time have been preceded by other types of wind and weather since Tertiary time.

HIERRO

This little island of only 278 sq km areal extension has, as may be seen from the map fig. 1.¹, a rather peculiar circumference. It gives the impression of the rudiment of a once existing rounded volcanic shield from which several sectors have been subjected to burstings and displacements.

We should need geophysical data in order to form an idea of what has happened here in the past. In the absence of such facts we must confine ourselves to suppositions more or less hypothetical in nature.

¹ Numbers in brackets give the site of the placenames on the corresponding map.

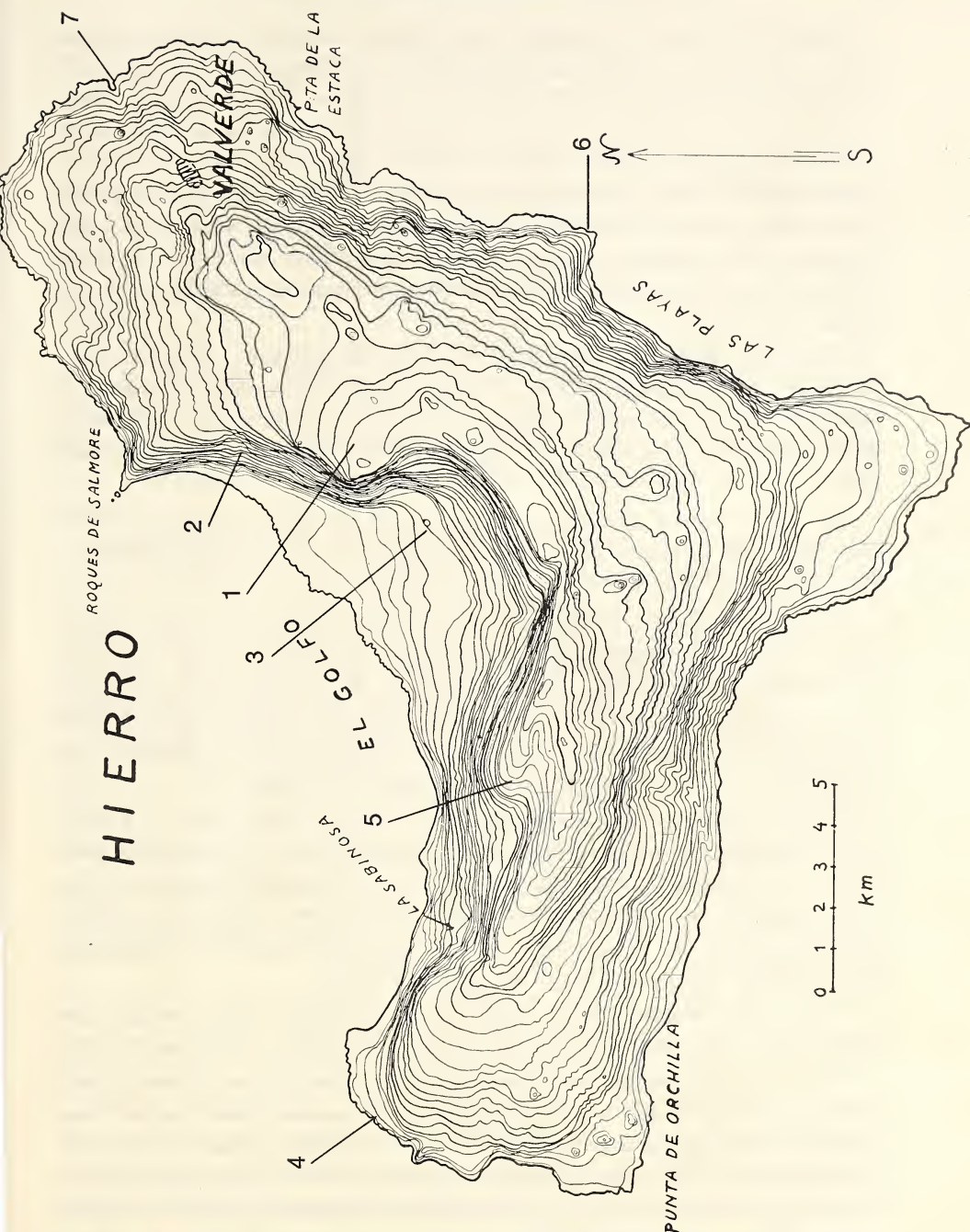


Fig. 1. Topographic map of Hierro with contour lines at 50 m intervals. 1 — Mountain corner of Izuque. 2 — Acantilado de Tivataje. 3 — La Frontera with the volcano El Campanario. 4 — La Dehesa with Arenas Blancas. 5. — Volcano Tanganasoga. 6 — Punta de Bonanza. 7 — Tamaduste. The bight of the south coast is called El Julian.

At first we have to consider the curious anomaly manifested in the great embayment in the northwest, El Golfo. This has been interpreted as a caldera or, better, as the remains of a great central caldera, from which all the volcanics of the island tableland have been emitted. But was there really a caldera here? The outward inclination of the lava banks from El Golfo, especially to the south, suggest a former eruptive centre here. But is the edge of El Golfo of circular form? The small map gives the answer: there is nothing to remind one of a crater or caldera edge. Instead we have a roughly rectangular confinement with many irregularities.

The edge begins in the north at Punta de Salmor. Then it runs south to the mountain corner of Izique (1). From here onwards it makes a bay to the southeast, then the continuation goes west-north-west to Dehesa. The »bay» is in reality the result of slumpings and rock falls.

No doubt here a great part of the island has gone, probably to the sea. The ancient centre of the island volcanic shield has been abolished! But what kind of forces have operated here?

The northern part of the edge from Punta Salmor to Izique seems to be a line of dislocation along which the land to the west has been depressed below sea level. It is Acantilado de Tivataje (2). The long profile represents a good cut across the ancient volcanic shield of the island in this sector. Later rock falls of course somewhat modified the escarpment, and there is at the foot an apron of scree.

The inner part of the embayment has much of the aspect of a head of great landslides, afterwards somewhat modified and enlarged by rock falls. It is, however, difficult to perform a closer investigation in this area, because later volcanic outbursts from some cinder cones have sent lavas down the slopes and covered most of the ground. The lavas have reached the sea shore along a large front.

There are several cones standing on different levels within the embayment, the most important being El Campanario at La Frontera (3).

From the SE corner westwards there is the long escarpment that ends in La Dehesa (4) or Arenas Blancas. This acantilado reminds one of that of Tivataje in the north, and one is inclined to think of a line of displacements. The edge forms the northern rim of the southern part of the island characterized by markedly southwards inclined volcanic strata. These strata are well exposed in the escarpment except where

younger volcanic cones have grown up and sent lavas down to the sea. The largest of these volcanoes is Tanganasoga (5).

It looks as if this southern part of the island forms a block that had been tilted separately.

How has the embayment been formed within this setting of dislocation lines the immediate cause of the opening of El Golfo? It must have been a series of landslides, and a great part of the island has in such a way gone down to the ocean, there probably continuing as turbidity currents directed towards the abyssal depths in the west of the island.

But in the wake of these mass movements there appeared a number of volcanic vents at different levels of the embayment. They ejected slags and sand and sent copious masses of basalt lavas down the slope, covering practically the whole area. These adventive volcanoes belong to a generation later than the (mostly larger) cones in the central upland.

In later times the border of the embayment, i.e. the edge of the interior tableland, was modified by rock falls and slumpings that are still going on. The circumference of the embayment is increasing. Some years ago a stretch of the highway that descends from the upper rim to the coast was blocked by movements of loosened rock debris. After clearing the roadside was reinforced by masonry constructions.

El Golfo is in fact a unique feature in the Canaries, nothing similar is to be found elsewhere in the archipelago. Perhaps the relative proximity of the Canarian Deep outside Hierro has provoked special conditions for such large-scale readjustments in the ground of the island.

If we now leave the El Golfo sector and follow the coastline of the island looking for other signs of landslidings, we have on the east coast a place that suggests another embayment of that nature although on a smaller scale. It is a rather semicircular embayment at the northern end of a coastal stretch called Las Playas, and it lies inside Punta de Bonanza (6). The diameter of this embayment is only 1.200 m and its walls disclose the lava series of the tableland on this side. It was first visited by K. von Fritsch (1894), who made some observations.

The confining wall is very steep (Risco de Hoya Verde) in parts, but later lavas coming from the upland and also scree have concealed some sectors in the exposures of the older rocks. It is difficult to decide if here displacements have caused most of the detracting of material to the sea, and if these have provoked landslides too. The entire east

coast of the island seems to have been controlled by dislocation lines, and the most apparent standing edge is here represented by the continuous wall of Las Playas, more than 1 000 m in height.

On the northeast coast there is a site called Tamaduste (7) where a small embayment appears, exposing the older formation of the island (basalts and trachybasalts). The low ground at the foot of the cliff has been overrun by recent basalt lavas from the volcano Tesoro nearby. This shore platform, the result of faultings seems to have provoked slumpings.

In short Hierro has been much reduced in circumference, and this has happened, it seems, at a relatively recent period. Dislocations have played an important role, but so also, it seems, have landslides, slumpings and rock falls, and the final result is a strongly demolished volcanic shield that once measured an extension perhaps twice that of the present one.

LA PALMA

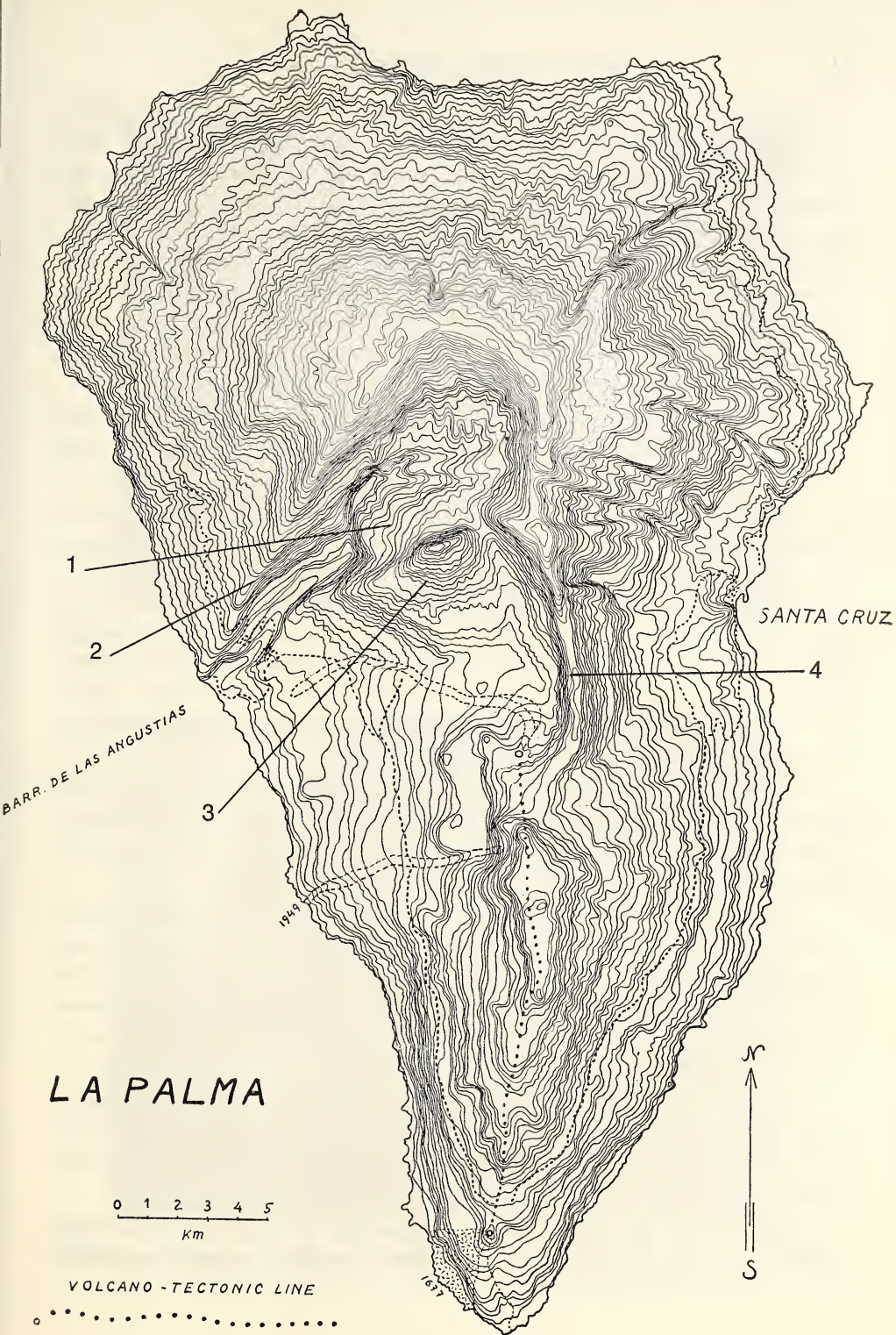
50 km to the north of Hierro there emerges the lofty island of La Palma with an area of 730 sq km. It has the shape of a pear with a northern head — a great dome — and a southern prolongation, a ridge that attains heights approaching 2 000 m. The island has generally steep sides, is much furrowed by erosion and is to a great extent forest-grown (*Pinus Canariensis*). It receives more moisture by the trade wind than the other neighbouring islands.

La Palma is in the surface mainly a basaltic island like Hierro. It differs from the latter having very numerous large and deep canyons especially in the northern dome, offering opportunities for study of the inner structure.

The many adventive cones are situated on all heights, and they are of different ages. They have sent lavas down to the sea, covering much of the ground, chiefly in Quaternary time.

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Fig. 2. Topographic map of La Palma with contour lines at 50 m intervals. 1 — Caldera de Taburiente. 2 — Escarpment of El Time. 3 — Montaña de Bejenado. 4 — Divide Los Andenes. The island is composed of a great northern shield much eroded by valleys and a southern prolongation marking the course of an additional volcanic zone of southward decreasing heights.



If we now examine the drainage pattern of the island, which forms a radiating system within the northern dome, we will find in the west a valley that offers a rather peculiar aspect. It is Barranco de las Angustias, which has its head in the famous Caldera de Taburiente (1) in the midst of the dome and runs west-southwest to the coast. This valley is in its whole length of a highly asymmetric aspect: the left side is relatively low ground sloping seawards, and the right side is a steep mountain wall called El Time (2). This extends to the coast with decreasing height. In reality the wall is a direct continuation of the northern wall of Caldera de Taburiente.

In the author's opinion Barranco de las Angustias and Caldera de Taburiente form a single problem complex. We may here briefly look at the geologic conditions in this sector.

Caldera de Taburiente is in reality no caldera of circular outlines: it is a valley head with several head canyons that have their confluence in a site called Dos Aguas. The walls are high, up to 1500 m, and steep, but the circumvallation is broken in the west and southeast. The southern sector of the wall is in reality a special mountain block, Bejanado (3). In the bottom of the Caldera a basement complex is laid bare, whereas the walls consist of a younger covering formation that constitutes the mantle of the dome. Rock falls occur repeatedly, especially in winter time from the precipices.

Barranco de las Angustias follows the Time mountain wall, but this is not the result of river erosion. The wall is a tectonic escarpment that continues into the Caldera. It is a geologic profile in this sector of the dome.

The left side of the barranco is a conglomerate wall that stands rather high in the entrance opening to the Caldera but soon decreases in height towards the coast. The material in the conglomerate is in the proximal part extremely coarse, but farther west the stones decrease in size and are better rounded. In the surface the conglomerate is capped by younger basalt lavas.

Barranco de las Angustia has cut its course into the conglomerate, and with the material extracted from it the river has built terraces on both sides of its course. The surface of these terraces diminishes with grade towards the coast.

In its whole appearance the conglomerate formation is an ancient gravel fan that was spread over the lower grounds outside the dome.



Fig. 3. One of the head canyons to Barranco de las Angustias within the bottom of Caldera de Taburiente. Looking south towards Bejanado. La Palma.



Fig. 4. The right-hand cliff where Barranco de las Angustias leaves Caldera de Taburiente. Here appears the unconformity between the basement and the overlying volcanic formation. A site of frequent rock falls. La Palma.

The spreading agent, however was not running water but apparently gravity itself. The conglomerate formation was deposited by large-scale landslides that emptied a sector of the dome, leaving as a hollow the Caldera.

These landslides were provoked, as it seems, by the displacements along the Time wall as a plane of movement that cut deep into the heart of the dome.

The avalanches were, however, the first (catastrophic) act of land migration. Then there followed long-lasting erosion along Barranco de las Angustias and its head gorges. The river destroyed in part the avalanche deposits and opened the erosion gorge that has given the valley its name. This downcutting into the coarse material by the river was going on simultaneously with a rise of the island; the base level was subsiding.

A part of the apex of the conglomerate fan is still conserved as a vertical cape pointing to the interior of the Caldera. The stones in this wall are extremely coarse and not rounded at all. The relatively insignificant waters of the valley cannot have transported these pieces of several tons consisting of the same rocks that form lava banks in the walls of the Caldera.

It is difficult to fix the time when these catastrophic events happened. The gravel material is already hardened so that huge vertical walls have been formed. Lavas of basalt from some cinder cones in the vicinity of the dome have been spread over the surface of the conglomerate, and these again have later to some extent been eroded. It seems probable that the avalanches took place at the end of the Pliocene period or at the beginning of Quaternary time.

If we make a survey of the remaining barrancos that furrow the flanks of the great dome we will find them all regular erosion valleys, mostly of great natural beauty. They have been eroded in the course of Quaternary time, most probably during the pluvials, when there must have been considerable rainfall. During this process lavas from many of the adventive volcanoes were cut across by the canyons. The longitudinal profiles are relatively steep since the heads lie at heights of ab. 2 000 m. The only exception is Barranco de las Angustias, counting from Dos Aguas to the coast.

Another sector of the island lying outside the dome in the proper sense is the intercolline room above the capital Santa Cruz de la Palma.

The bottom of this depression grades to the east coast at an angle of ab. 10° and is covered entirely by basalt lava flows in regular succession. To the west of this depression there rises the dividing ridge of Los Andenes (4), an erosion-furrowed divide of older volcanic material.

The author has considered the possibility that the depression of Santa



Fig. 5. The Time escarpment that accompanies Barranco de las Angustias on its right side down to the sea. The lower slopes consist of gravels. La Palma. Looking west.



Fig. 6. The Lavanda upland depression against the main divide. Los Andenes, a probable detractor area of landslides. La Palma

Cruz might be interpreted as an ancient landslide area subsequently filled with lavas to a certain amount.

The above mentioned divide, Los Andenes (that to the east is intensely eroded into ravines) exposes to the west an unbroken slope facing the depression above El Paso. The conditions are suggestive of the head region of great landslides to the west along the stretch now used by Barranco Hermosillo. As a limit to the south of the sliding lane Montana Enrique stands with its precipice. This mountain is of a trachyte rock, an islet in the midst of the basalt lava streams that later on have covered the region.

Rock-falls are numerous in the island, the most spectacular within C.de Taburiente, which is surrounded by nearly vertical walls of more than 1 000 m height. Here rock-falls happen every winter time when precipitation is frequent. Part of the fallen material accumulates to form a scree, and part is dragged by the temporary streams into the river beds of the head system of Barranco de las Angustias.

GOMERA

This small island of 380 sq km area is cake-formed and rises to heights of 1 500 m. The coasts are generally steep and inaccessible except where the barrancos have their mouths and a kind of playa is formed. Like Hierro this island seems to be a last remnant of a once much wider insular shield of volcanics. Especially to the north there may be a lack of land, likewise to the west. One may suppose that at least one half of the primeval island has disappeared into the sea.

The geologic structure of Gomera (see Hausen 1971) differs to some extent from that of Hierro and La Palma. We have here in the north large exposures of a basement supporting a younger volcanic formation that covers nearly the entire island, especially in the south where the basement is invisible. The basement composed of pillow lavas, basic plutonics and an immense number of dikes is, as stated already by C. Gagel (1925), in a more or less decomposed state, whereas the overlying basalt formation has a fresh aspect. Both complexes are penetrated by phonolite and trachyte intrusives forming sills, lakkoliths, volcanic necks and also superficial lava sheets.

The island is drained by a radiating system of barrancos cut deeply into the structure. The northern half is more intensely eroded with

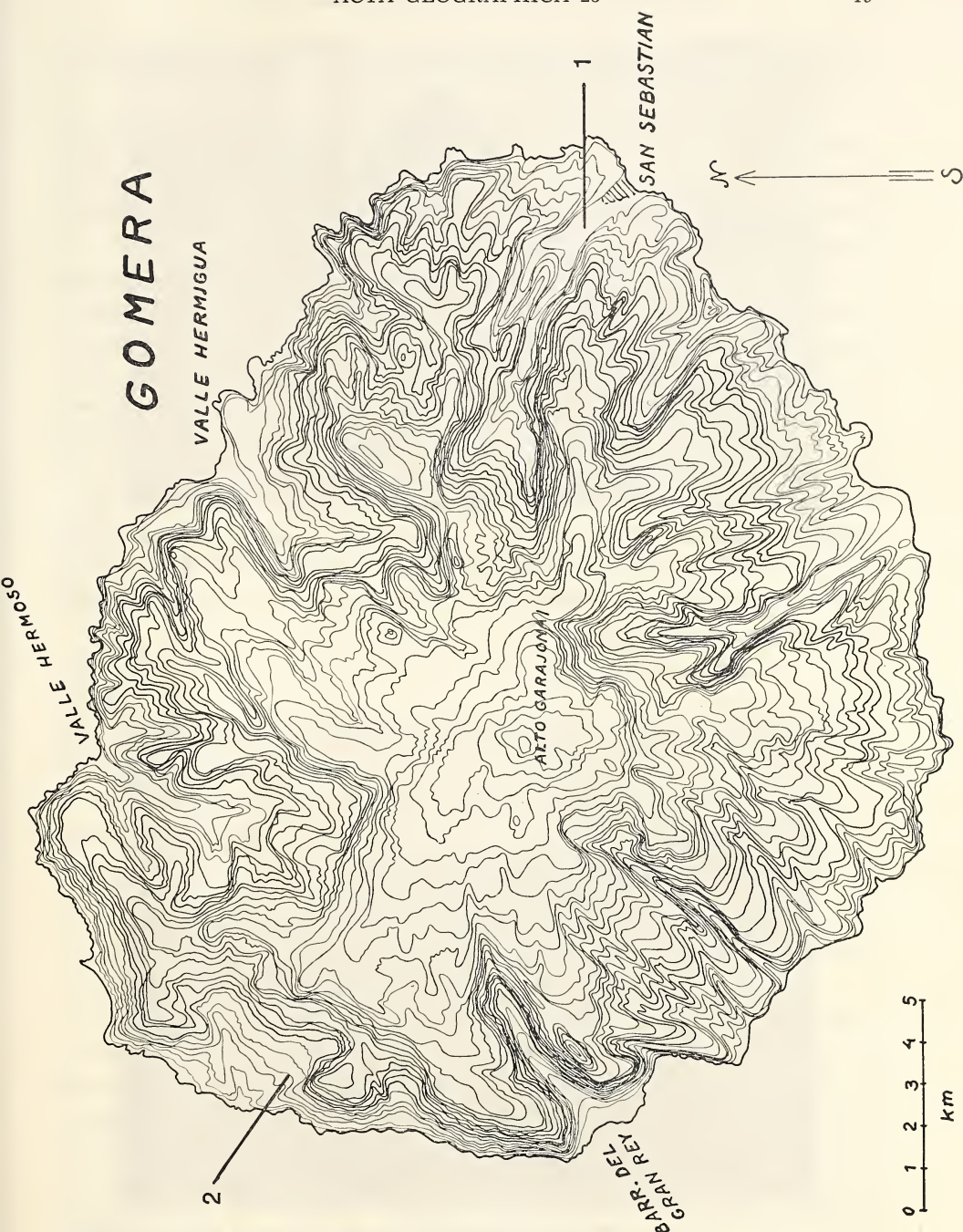


Fig. 7. Topographic map of Gomera with contour lines at 50 m intervals. 1 — Baranco de la Villa. 2 — Region of Alajeró. — The island displays a kind of damaged volcanic shield, eroded by a radial pattern of barrancos. More recent volcanic forms are lacking.

branching valley systems, whereas in the south there are more widely spaced canyonlike barrancos.

The influence of the trade wind makes the northern half more humid with a cloud in the higher regions, the southern declivities being more in the shelter with much sunshine. The upper regions in the northern half are covered with a forest of *laurisilva* growing in a soil of considerable thickness.

The large valley systems in the north have been eroded across the cover of the younger volcanic formation and further deep into the basement of the island. It is evident that in this process of excavation slumpings and landslides have cooperated from time to time, in other cases the valley systems would not have been so broadly developed. It is not possible to indicate the sites of particular landslides, weathering and erosion have destroyed too much. The only apparent signs of former landslides and rock falls are the sharp edges in the upper surrounding regions. In the course of this valley-making process huge masses of debris have been carried to the sea and have disappeared. But the phonolite necks have been left standing as the most resistant parts of the ground.

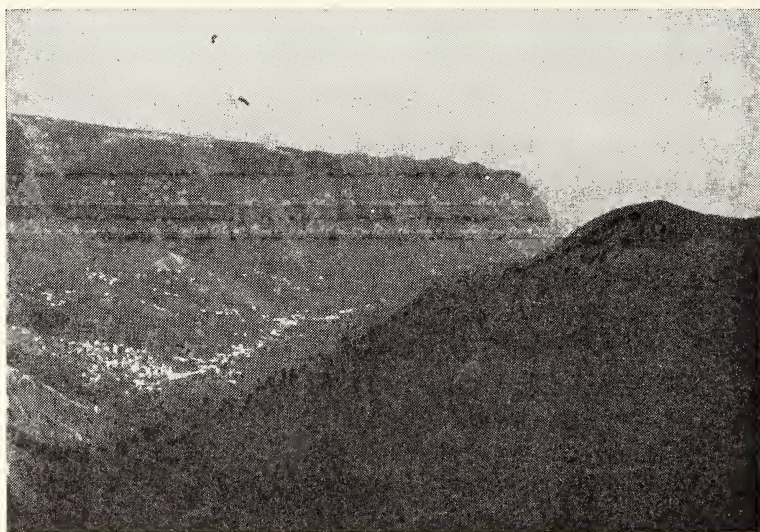


Fig. 8. Valle Hermigua, one of the large valleys on the north side of Gomera. Looking northwest from a head canyon.



Fig. 9. Roque Agando, a phonolite neck in the midst of an erosion landscape at the head of Barranco Santiago. Looking southeast. Gomera.

An area of extensive land sliding lies in the west between the mountain edge of Arure and the coast, also further north. Great masses of both the basement rocks and the covering younger volcanic formation have gone to the sea, leaving behind a slope now furrowed by some smaller barrancos.

In the southern parts of the island no landsliding phenomena have appeared as far as I have seen. But there are numerous sites of rock falls partly on a grand scale, as, for inst., at El Paso in the vicinity of Alajeró (2). Here a huge phonolite lava stream has consolidated, but its lower part has subsequently been torn off by rock fall. In this way a precipice has been formed of the phonolite mass with scree at the foot, resting on subjacent basalts.

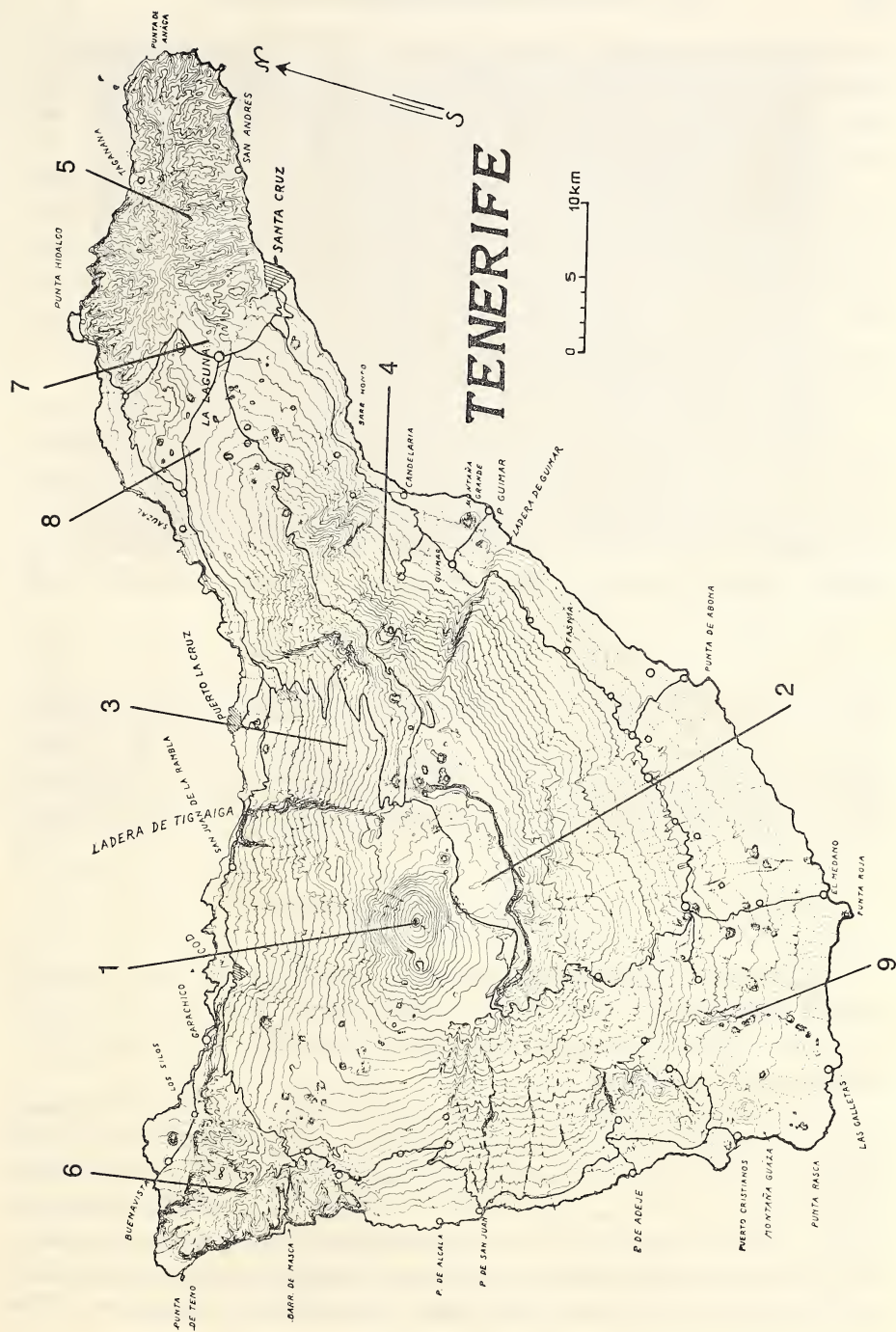
Along the two tectonically controlled valleys of Santiago and Barranco de la Villa (1) there are frequent cases of rock fall along the steep sides. Part of the debris has of course been carried away by running water in times of rain and left accumulated in the train of the valley down to its mouth. Good examples of rock fall are to be found in the sites where volcanic necks are standing above eroded ground. Jointings in the monolith facilitate the drop of debris that has accumulated as an apron of scree around the neck.

In short: Gomera offers examples of all kinds of gravitational adjustments in an exogenic sense (except solifluction) and the processes are intimately connected with the work of erosion and marine abrasion, especially on the windward side. Most of the waste has in the course of time been carried away to the sea and disappeared, forming a kind of shelf surrounding the island. It is remarkable that a younger adventive volcanism has not appeared here (with a few exceptions) so we have ample opportunities to study the exogenic phenomena without the intervention of later lava streams and the deposition of vast covers or pyroclastic material. Owing to this Gomera gives the impression of a relatively old island completely surrendered to the exogenic forces.

TENERIFE

This central island in the archipelago measures 2 058 sq km in area and is the highest of all with max. 3 711 m [Pico de Teide (1).] The island rises from a deep sea of $> 3\,000$ m and the coasts are steep especially along the windward side. The geology of Tenerife is rather complicated (Hausen 1956), offering different media for the exogene attack. The relative, most ancient is a basalt formation in the Teno and the Anaga peninsulas with lavas in flat position and an abundance of pyroclastics. Besides, there are numerous dike systems. These headlands are, as it seems, the remaining parts of an ancient island composed of basaltic volcanics but penetrated by dikes, sills and necks of phonolites. — Upon this fundament there rests a great volcano of the stratiform type with an ample caldera in the culminating part. This central volcano is composed partly of salic, partly of basic lavas and pyroclastics. Within the caldera there has later grown up a twin cone, Pico de Teide — Pico Viejo, consisting of trachy-phonolitic glassy material and pumiceous strata. (1) As younger elements in the island structure there are the numerous cinder cones of alk.basalts, scattered

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Fig. 10. — Topographic map of Tenerife. Contour lines at 100 m intervals. 1 — Pico de Teide. 2 — Caldera de las Cañadas. 3 — Valle de Orotava. 4 — Valle de Güimar. 5 — Peninsula de Anaga. 6 — Peninsula de Teno. 7 — Valle de La Laguna. 8 — Valle de Guerra. 9 — Montaña de Jama. The island is composed of various geologic elements: a central stratovolcano crowned by Pico de Teide (as a younger summit) and older parts of mostly basaltic nature in the northeast and west, partly also in the south. Young volcanic cones are strewn over the island.



on different levels. Their lavas do cover much of the surface. A special formation consists of pale-yellowish pyroclastics of phonolitic composition, the origin of which might be sought in the central orifice and antedating the upbuilding of the Picos.

Tenerife consists of material of very different composition, specific gravity and structure. We must confess, however, that we do not know much of the interior of this lofty island. Up to date no signs of a basement complex like that in La Palma and Gomera has been found. Probably this basement lies so deeply buried under the masses of younger volcanics that there is no chance to have it exposed in deep erosion furrows.

As a very lofty island Tenerife offers an obstacle to the trade wind and a zone of greater moisture is formed in the upper slopes of 800—1 000 m. The summit region is generally dry, but in the leeward upper slopes again some moisture is retained. The long southern slopes are relatively dry right down to the sea shore. But it is evident that in former times the condition were different, with running surface water on both sides of the island.

The loftiness of the Tenerifan volcanic edifice must mean that instabilities have been present in many parts and at many times in the course of the upbuilding. With the degree of loftiness there followed greater dimensions of mass movements. We may at first look at some of the most remarkable features in the morphology and see, if arguments can be used in favour of exogene adjustments of the volcanic masses.

Caldera de las Cañadas (2)

This famous summit depression of the island has long been the subject of dispute as to how it has come into being, if by way of erosion or by a collapse in connection with great explosions like those in the Indonesian volcano Krakatoa.

Las Cañadas is not a closed depression, and it is filled with lavas from the twin volcanoes that lie within it. In fact there is not one depression but two; one easterly and another in the west, the latter called Llano de Ucanca (the bottom of which lies 2 000 m above sea level). The two depressions are separated one from another by a very tattered ridge called Peñones de García running NE from under Pico de Guajara into the base of the Teide cone, where it disappears. The



Fig. 11. The southern escarpment of Caldera de las Cañadas, Tenerife. Looking west towards Pico de Guajara.

eastern depression lies somewhat higher and is much more filled with lavas from Teide.

The area of Las Cañadas is surrounded in the east and south by an escarpment somewhat eroded and with several tops. Here in the walls facing the caldera the volcanic strata are well displayed (i.e. above the limit of the talus). Here is in fact a zone of rock falls (fig. 11, 12).

Here is also a break in the chain called Boca de Tauze, the former outlet of a lake. — Another sector lies in the north called La Fortaleza, but it is very short. Between that wall and the eastern sector there is a wide opening — El Portillo that leads down to the Orotava valley.

It is evident that the walls mentioned represent cuts into the structure of the central volcanic cone. One can see how the walls pass across several valleys that once led down from the summit of the great cone. The former hydrographic centre has been lost. Instead there opens now the wide Caldera de las Cañadas, completely filled with younger volcanic products.

Some years ago D. J. MacFarlane and W. I. Ridley (1968) carried out a gravity survey of Tenerife, establishing 133 observation stations all over the island to get a better insight into its inner structure. One



Fig. 12. A part of the southern wall of Caldera de las Cañadas at Llano de Ucanca. 2 000 m above sea level. Looking west. Tenerife. Weathering and rock falls have altered the scarp.

of the main results was that within the great caldera there are values of positive anomalies instead of negative ones that would have been expected in case of a collapse caldera (like Krakatoa). The authors conclude therefore that the formation of the caldera must have taken place not by volcanic action but by landslides on a grand scale. After the catastrophic events new volcanoes started within the affected area: Pico Viejo- Pico de Teide — with their lavas and slags filling the entire detraction area and also sending lavas down the runway to the north.

The present author has tried to reconstruct the course of these slidings, (compare with the accompanying map fig. 10). There seem to have existed two lanes of landslides, one with its head in the southern sector as far east as Pico de Guajara; another detraction area had its head in the eastern sector and in La Fortaleza. Both runways joined one another below Montaña del Cabrito. The common lane had a breadth of 10 km and reached the sea where now Bahía de San Marco is situated. The topography here is of a very curious kind, an assemblage of hillocks in complete disorder of transported rubble of volcanic material.

The later lavas from Picos have to a great extent covered the lane in question. The underlying ground can, however, be studied by way of water galleries. Most of the material slid down to the sea and has disappeared from sight, but the fact that it is there, can be found from the sea chart.

Within the head region of the landslides there remained a remnant of the central volcano in the shape of a row of weathered hills the mentioned Peñones de García. This stretch separates the two head regions.

The Orotava valley (3)

Apart from the above described landslides another of large dimensions occurred in the vicinity creating the present (now lava covered) Valle de Orotava (see map fig. 10). This valley is confined in the west and in the east by scarps: Ladera de Tigaiga and Ladera de Santa Ursula. Whether these scarps are actual faults has not been fully established although Tigaiga at least appears to be creating a straight cutting geologic profile across the northern flank of the old strato-volcano (of pre-caldera age). Within these limits there opens a wide densely populated valley reaching from a treshold at El Portillo down to the sea. There exists in the ground of the valley below the superficial lava sheets a kind of fanglomerate that may have played the role of a lubricating sheet for great masses that slid down. On studying the head region more closely one will find signs of mass detracton in certain places such as Los Organos (above Aguamansa). Here a vertical wall of several hundred m height has been left standing: it consists of rather brittle pyroclastic material dissected by innumerable vertical dikes (hence the name). Farther southwest the head of the valley approaches the Caldera without entering it. There must have been formed a kind of divide between the two areas of sliding.

In times succeeding these happenings volcanic outbursts took place at different levels and the lavas erupted covered all the ground of the valley.

The Güimar valley (4)

On the opposite side of the main divide of the island (Pedro Gil) due east of Caldera de las Cañadas there opens the Güimar valley

which has much in common with the physiognomy of the Orotava valley. The main difference appears in the drier aspect of the former region owing to its situation in the leeward side of the island.

The Güimar valley is confined in the southwest by the so called Ladera de Güimar that recalls somewhat Ladera de Tigaiga. In the flank of the main ridge of Pedro Gil, in the head region, there are deep embayments. In the northeast the valley ends at the foot of a mountain ridge that emerges from Pedro Gil forming a kind of Ladera. Here some complications are seen in the topography owing to the presence of erosion valleys.

The Güimar valley is wide and has a rather steep grade to the coast. The whole aspect is that of a former mass movement area with several signs of detractation in the head region. There is no certainty if here also faultings have been at work. Ladera de Güimar may in that case be a great scarp.

As is the case with Valle de Orotava the Güimar region is entirely covered with a carpet of younger volcanics, first by bright yellowish lahar deposits, then by black basalt lava tongues that have been emitted from some cones. The valley ground can owing to that not be studied by immediate observations.

In examining the topography of Tenerife in other parts one cannot escape the impression that exogene gravitational adjustments must have operated in many places although immediate proofs are difficult to present, since later erosion and later adventive volcanism have contributed to make the vestiges of rock slippings uncertain. A problem of this kind is offered by the so-called La Laguna valley (7) in the Anaga peninsula (5), where the bottom lies 500 m above sea level. Either it is a tectonic depression or the head region of landslides in a time antedating the many adventive volcanoes that with their lavas have covered the ridge off the mouth of the valley (ridge of La Laguna). The author is inclined to believe that landslides occurred on both sides of the ridge in times before the adventive volcanism in this region. Reconstruction is, however, now impossible to carry out. The same may be said of Valle de Guerra (8) to the north of the La Laguna valley, where the small city of Tegina is situated. This valley is in the north-east confined by a ladera, and a somewhat lower one is to be found in the west, where the highroad to Orotava passes nearby.

Going over to the northwestern extremity of the island, the Teno Peninsula (6) we find a peculiar depression within the basaltic terrain

called Valle de Palmar. Its bottom lies ab. 500 m above sea level and it is surrounded by mountain sides except in the north, where a portillo exists, apparently one of more ancient date. Whether mass movements due to gravitation have happened here is uncertain, since younger volcanics have filled the bottom and later erosion has deepened the passage in the north.

In the large southern declivities of Tenerife there are several valleys of flat configuration, opened wide to the south and populated (in parts). It is conceivable that at least some of them, like Valle de San Lorenzo, have been the theatre of slidings. Otherwise it would be difficult to explain, for inst. the presence of the sharp ridge Montaña de Jama (9) between San Miguel and San Lorenzo. Somewhat mysterious also is the Santiago valley in the west separating Teno from the central mountains. It has a broad bottom and is on both sides confined by mountain slopes (already somewhat eroded). The bottom is filled with young lava streams. Its head is strangely circular and steep walled, reminding one of a landslide detraction area. The valley runs down to the coast at Puerto Santiago.

Of rockfalls there are plenty of examples in Tenerife, many still happening especially in the southern part of the island, where the climate is more dry and the insolation stronger. Numerous are the rock falls also in the Cumbre region, where during winter time the temperature drops below zero. The road department has much trouble in clearing the way for vehicles along the long Cumbre road between La Laguna and Las Cañadas. Rockfalls are common also in the Anaga and Teno regions with their very accentuated relief due to erosion and marine attack.

GRAN CANARIA

This rounded island has an area of 1 532 sq km and has been called a continent in miniature. It is in the main shield-formed with central elevations reaching nearly 2 000 m. The slopes are furrowed by many barrancos in a roughly radiating pattern. The coasts are steep in the west and partly in the south, otherwise there are more open sandy beaches and flat coastal lands. In the northeast there is a smaller peninsula, La Isleta, consisting of younger volcanics. (See Appendix map fig. 13)

Gran Canaria is in the main a relatively old island, as is manifested

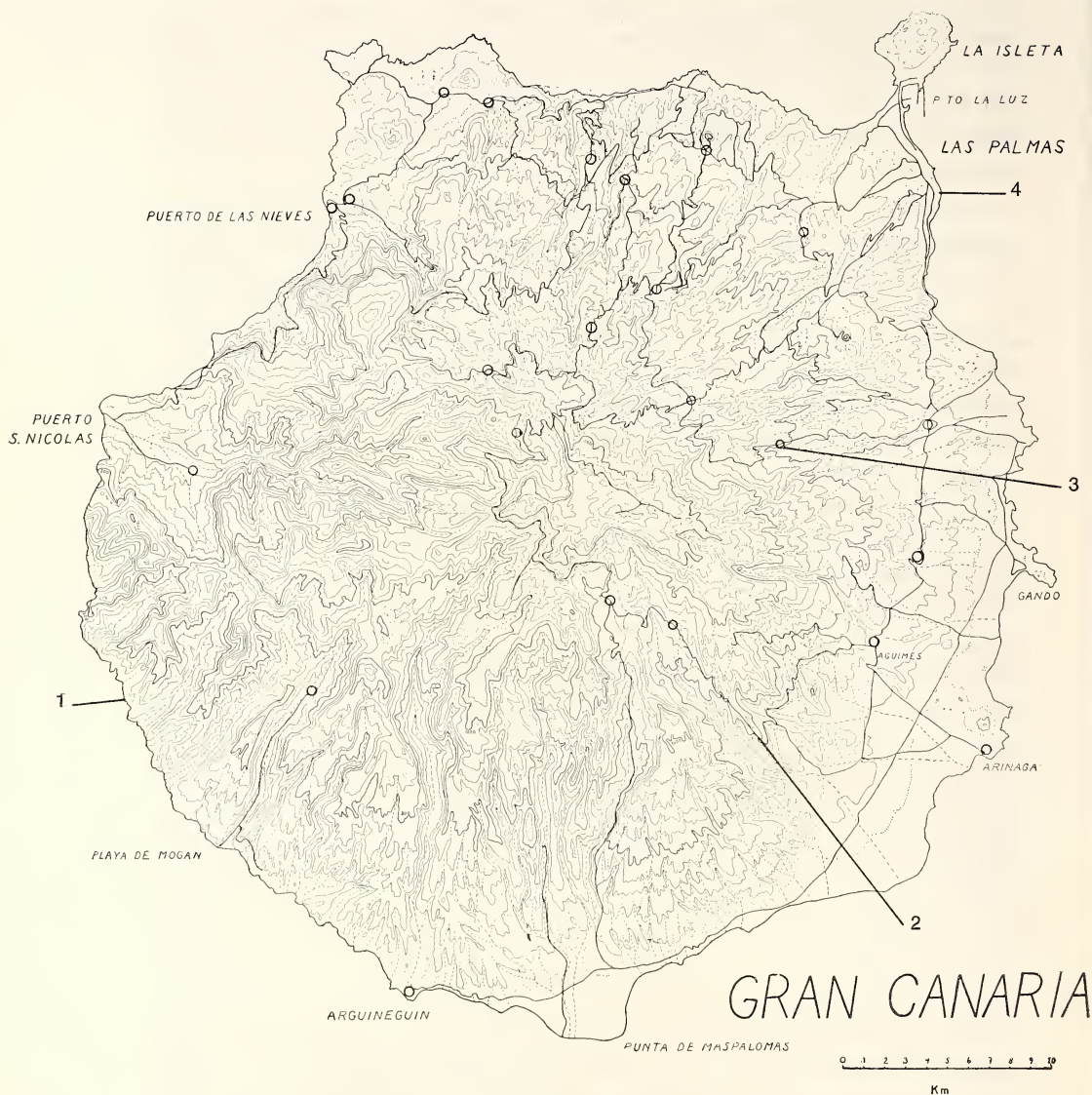


Fig. 13. Topographic map of Gran Canaria with contour lines at 50 m intervals. 1 — Barranco de Tejeda, 2 — Barranco de Tirajana, 3 — Barranco de Tenteniguada, 4 — Barranco de Guiniguada. The island is shield-formed but has a very complicated structure with many different rock complexes and centres of eruption. An old central caldera is already half destroyed. More recent volcanic cones are relatively sparse, erosion forms dominate.

by the deeply eroded state of its slopes. Younger volcanic forms do not disturb this general impression.

The geology of this island is rather complicated, and one can say that it consists of many volcanic constructions placed one upon another and separated by unconformities. That means the island has passed through times of vigorous volcanic activity and times of exogenic work. In recent time the latter agents dominate, or more exactly they have made the work of running water (now practically non-existent). Volcanic activity faded away already long before the arrival of the Spaniards at the island. The last eruptions, on a small scale, were confined to a few points.

This is not the place to describe all the geologic features of the island. It may only be mentioned that a basement complex like that in La Palma, Gomera and Fuerteventura is not visible. The relatively oldest formation is a basalt series appearing in the west. Later formations comprise phonolites, ignimbrites and basalts and a capping sheet of an agglomerate that has been much dissected and abolished by later erosion. Finally there are the younger basalt volcanoes.

Of interest in our treatise are three great erosion embayments, those of Barranco de Tejeda, Barranco de Tirajana and the valley of Tenteniguada. They represent types of erosion recalling somewhat the northern valleys in Gomera, but are more impressive phenomena. They include stages of gravitational adjustments on a greater scale.

Barranco de Tejeda (1)

This is a large, deep drainage system that has penetrated into the very heart of the island. It has its head not far from the culminating region with the gorge of La Culata. From here a canyon can be followed along the bottom of a wide and steep-edged valley to the west coast, crossing on the way a mountain barrier in a wild gate, a morphologic anomaly difficult to explain. — The middle course of the river runs along the bottom of the wide valley that could be called a caldera by simple vista, and it has also been interpreted as a volcanic caldera, ultimately by H. U. Schmincke (1968). The history of the creation of this caldera is, however, so complicated that the topic remains outside the aim of this paper. We may here consider only the prevailing morphologic circumstances.



Fig. 14. Piece of rock fallen from the edge of a phonolite cliff in Barranco Escusebarajas, tributary to Barranco Arguineguin, Gran Canaria. Photo T. Bravo.

The wide room of the caldera-like valley is confined on both sides by steep rock walls consisting in parts of agglomerate of the Roque Nublo formation, in parts of alk.basalt lava series. Lower down the

slopes towards the river canyon there are many different beds of volcanics, generally of lesser resistance. From time to time rock falls from the edges, also slumpings take place. At present there is little rain within the caldera, and insolation makes the rocks brittle and crumbling. It is difficult to state how many of the morphologic features are the result of old volcanic collapse movement, and how much has been formed by exogenic alterations. Large slopes of debris on both sides of the great depression speak of powerful surface modifications in the standing volcanic structures. Barranco de Tejeda itself is a canyon apparently from Quaternary time, and its downcutting work is intimately connected with the opening of the break-through, the gorge in the barrier before entering the coastal plain of San Nicolás de Tolentino.

The young river canyon has received numerous tributaries, the most important being Barranco de Siberia (from the left). The divides in the area between this barranco and that of Tejeda form a mountain complex crowned by spectacular erosion witnesses (Roque Bentaiga). The entire area presents a stage of the wildest exogenic destruction.

Barranco de Tirajana (2)

This is a large drainage system in the southeastern sector of the island, and like that of Barranco de Tejeda it narrows towards the coast. The upper reaches form a wide amfitheatre-like embayment into the highland. At the northern end there is the highest point of the island, Los Pechos. The upper region of the valley is a widely branching system of (now dry) barrancos that unite into the main river of Tirajana. This latter continues to the sea in a narrow gorge cut into a basalt lava fill in an old valley of possibly tectonic origin.

The head region is the stage of exogene rock destruction and mass movements beginning in the steep confining edge that consists in parts of the R. N. formation, in parts of basalts. Huge masses of boulders have from time to time dropped down the slopes and crumbled away. The region has earlier been interpreted as a volcanic caldera, but it seems evident that only exogenic forces have here been at work. In these destructive processes ground water seems to have had its share, making the strata in the slopes partly lubricating. Landslides on a minor scale happen still in our days, like that described by F. Macau Vilar (1956) from la Rosiana in the region of Santa Lucía in the lower part of the



Fig. 15. A slope of slumping rock debris in the northern side of the drainage area of Barranco de Tirajana. Southern part of Gran Canaria. Looking northwest.

head region. A highroad bridge was demolished and houses were damaged by an earth flow from the eastern slopes into the valley.

The denudation process within the Tirajana area has been lengthy, apparently beginning in the Quaternary period and interrupted by volcanic outbursts like those filling the lower course of the Tirajana valley with lavas now cut across by a canyon.

It is not possible to state if the head region of Tirajana has been the stage of *great* landslides in the past. The whole morphology speaks, however, in favour of some catastrophic mass detracting that gave birth to the curious semi-circular ambayment in question. (fig. 15) Later slumpings and erosion have obscured the original conditions. More detailed investigations might be necessary to win a better insight into the problem.

Valley of Tenteniguada (3)

In the eastern sector of the island there opens a wide mountain valley, and here the village of Tenteniguada is situated. It is the head region of some mountain barrancos that come down from the highland

nearby. Great precipices have been formed of a similar type to those which surround the head of Barranco de Tirajana. But here are also some standing phonolite necks like Risco Hernández (fig. 16) giving special beauty to the landscape. Also this region has been subjected to rock falls on a grand scale and slumpings of weak masses of debris; numberless boulders of different sizes lie around in the lower slopes. Most of the transported waste has been carried down along the valley to the east, forming in parts smooth grounds now cultivated.

By the opening of such embayments as that of Tirajana and Tenteniguada the central highland is being reduced in circumference in a most effective manner, reminding one of the effects of glaciers with their kar-forming actions.

Apart from the three cases of vigorous mass detracton in the island there are the many barrancos of more ordinary Canarian type that drain the island in different directions. They have all been formed in the Quaternary period of greater rainfall — now they are dry. Erosion has continued vigorously in them all in the relatively loose volcanic material, and *saltos* (waterfalls) have not been developed. The walls of the barrancos are generally steep to vertical, and rock falls are frequent, also landslides (Barranco de Fataga). A case of large rock fall is illustrated in the fig. 14. The gravel carried away by the rivers has mostly been deposited in the lower course of the valleys, deltas have seldom been developed. A singular case of delta-like deposition is treated below.

One can state that the erosion process of Grand Canary has reached a state of middle maturity in some zones, whereas in other regions it is still young attacking from all sides the remaining parts of the central highland that lie over 1 500 m. What we see now is, however, only the latest erosion cycle; that was of course preceded by others, intervening between periods of volcanism in the history of the island geology.

Las Palmas terrace and valley of Guiniguada (4)

Finally we may transfer our attention to the northeastern sector of the island, where rather curious conditions in exogene geology are to be seen. I refer to the so-called Las Palmas' terrace, a thick sedimentation platform roughly fan-shaped and of Miocene age. This deposit has apparently been formed under water to a height of more



Fig. 16. Home of the rock falls. Risco Hernandez, region of Tentenigunda, east side of Gran Canaria. Looking southeast.

than a hundred metres and the material is of varying composition. Coarse- and fine-grained gravels are present, likewise lime deposits, and many fossils are encountered here.

This terrace has a rather wide extension with the apex directed towards the lower course of the Guinguada valley. This valley is one of the oldest in the island, and it is thought that much debris must have been carried down its course in the past. The same can be said of most of the other larger valleys in the island; the only exception is that Guinguada seems to have left much more deposits than is the case elsewhere around the island coast. For instance, Barranco de la Virgen is an impressive valley running along the windward slope where moisture has been abundant, but at the mouth of the valley there is not much sediment to be seen.

The deltaic deposits of Barranco de Guinguada are, as said, from the Miocene period and those of Quaternary valleys are insignificant. There must have been a period of great material transport along Guinguada in that remote Tertiary time. But was it really a river trans-

port one may ask. In this northeastern sector a formerly existing formation is apparently missing, and that is the cover of the chiefly phonolite formation. This cover of great thickness was expanded once over these areas. Now there are only sparse remnants left in the summits of the ridges between the valleys. Can this cover have delivered the material necessary for the deposition of the Las Palmas' terrace? If so, could avalanches have contributed to the transport towards the coast? These are questions still to be answered by examining the material of the terrace. It is apparent that special conditions lie behind.

FUERTEVENTURA

This large island lies to the northeast of Gran Canaria, separated from it by a sound 1 500 m depth. It has an area of 1 725 sq km and is a relatively flat island with heights seldom reaching > 600 m. An exception is formed by the southwestern extremity, Peninsula of Jandía, that has summits reaching 800 m. The relief of the island is that of a Mittelgebirge with rolling hills and open valleys, here and there narrowing to a canyon. The coasts are generally low, but rocky, except where rivers end. The island is divided into two parts by a broad longitudinal valley, and that division refers also to the geologic structure.

The western half consists in the main of basement rocks of a sedimentary series (P. Rothe 1968) intruded by a host of steeply dipping dikes chiefly of basalts that have a constant NNE direction and give to the whole basement a feature of anisotropy. There is very close spacing between the dikes, so a great stability must be attributed to the whole complex. There is, however, in the middle sector of the zone in question an area of plutonic intrusive bodies with surface forms of their own. The eastern part of the island consists of a great number of more or less isolated hills of a flat-lying basalt formation of later age, consisting of both lavas and tuffs with a number of dikes. Between the hills there are broad gaps of lower ground, connected with the longitudinal valley. In the west there are flat-lying banks of a limestone formation.

The peninsula Jandía consists of the basalt formation that occupies the eastern half of the island, forming here a continuous chain, but this

is separated from the mainland by a broad shallow isthmus (sand-covered).

A younger adventive basalt volcanism has placed a number of cinder cones in different parts of the island, especially in the northern end and in the middle sector of the longitudinal valley.

Erosion has worked vigorously in this geologic structure for a long time forming the mentioned Mittelgebirge relief, and creating also great accumulation of sands in the bottoms of the valleys.

The subdued relief dominating most of the island does not produce conditions favourable for landslides, except in one part — the windward side of the Jandía peninsula. Here we have slopes of several hundreds of metres cutting across the volcanic strata that have a southerly dip of some degrees. From time to time masses have slipped down the steep slope to the foreland at the coast, and that process seems to have continued for a long time, because barranco erosion has not been able to develop. In the opposite side of the ridge the conditions are different: the grade is more gentle and barrancos have been cut into the rocky ground ending at the sandy coast.

The mass movement that dominates in Fuerteventura is the rock fall from the slopes of the eastern erosion mountains, which has accumulated broad foothills of scree. In the western mountains the slopes are almost entirely covered by rock waste of angular stones in a constant creep downhill, excellent examples of this phenomenon under the influence of dry climate.

Along the Barlovento coast one will find rather long stretches of low cliffs in the basement formation of 15 m altitude. Here rock falls are common.

Fuerteventura is as mentioned, a region of mature relief where the exogenic agencies have worked probably since the end of Tertiary time and under changing climatic conditions. The subdued relief was established already before the time of the volcanic activity that created the many cinder cones. These stand out as relatively fresh morphologic elements amidst the worn-down mountain ridges. Certainly the island passed through an age of energetic erosion creating acute landforms and also possibilities for landslides under humid conditions. That time is, however, far back in the island's geologic history.

Fuerteventura differs from all the other Canaries in respect of sedimentary accumulations. The longitudinal valley contains stretches of sand and gravel in thick sheets, and wide plains of sand are to be

found in the region of Gran Tarajal and elsewhere. Also along the mountain valleys there are similar accumulations. Many of the coasts are sandy with broad playas.

LANZAROTE AND THE ISLETAS

The farthest member of the archipelago in the northeast is Lanzarote with its small islets lying around. The island has an area of 796 sq km and is relatively low; the greatest elevations lie in the north with max. 610 m. The coasts are generally low and sandy except in the northwest, where we have the long cliff of Famara facing the sound of El Rio, that ends in the north with the cape of Los Fariones.

Lanzarote is an island that has been subjected both to displacements and erosion, and finally also to later volcanism on a grand scale. There is a highland in the north with an erosion relief of middle maturity, and a similar landscape appears in the south called los Ajaches. The middle part of Lanzarote is occupied by a lowland filled with a great number of volcanoes of relatively recent age and with their lavas. A lava front at the west coast measures 5 km in length.

It is evident that Lanzarote in the past was united with Fuerteventura and they formed together a landscape of mature relief. Originally it was not so, in its youthful stage erosion had created systems of gorges and a broken relief. But the denudation progressed, open valleys were formed and much sediment was deposited in the valleys and along the coasts. So the phenomenon of land sliding belonged to a time past.

In the northern highland of Famara we can still observe the remains of a relatively mature relief trending east from a watershed that has been badly attacked by fractures and erosion, so that it is missing in some parts. The same can be said of the watershed of Los Ajaches in the south.

Landslides and rock falls can actually be studied in the cliff of Famara, although on a smaller scale.

That Acantilado de Famara is a fault scarp is evident from the fact that Graciosa lies to the west, forming a barrier towards the ocean. In the south Acantilado de Los Ajaches has a foreland of undulating relief. It is also a subsided part along the fault of the land mass.

Fuerteventura and Lanzarote seem to be the relatively oldest islands in the Canaries; they were probably in the past united with the African continent. Erosion has here progressed farther than in the other islands, including Gomera, so the final result has been the open undulating relief of both islands, somewhat modified, it is true, by fracture displacements. The exogene gravitational adjustments are here principally limited to rock falls from some cliffs left standing and to creep of the debris that covers the slopes of the hills. The rain wash is under present climatic conditions very sparse. It may happen in time of occasional winter showers, when the transport of material is facilitated by the lack of a protective vegetation cover. It can thus happen that the water dams constructed especially in Fuerteventura are filled with gravel and sand, thus destroying the dam function. But in main the transport of the waste has ended already in Quaternary time, when precipitation was far higher than now.

In the general picture offered by the Canaries Fuerteventura and Lanzarote stand out as exceptions. They have passed long ago the stages of general instability of the volcanic ground. A curious circumstance to be mentioned is the fresh volcanic activity that has attacked especially Lanzarote, where lavas have been erupted on a scale unknown in the other Canaries (of recent age). These lavas are so widespread that they have concealed the old erosion relief in a great part of the island. Thus the island offers striking contrasts in its old relief side by side with the youngest lava fields and volcanoes. In Fuerteventura this young volcanism did not reach such proportions; here the old surface still dominates the landscape.

About the *Isletas Graciosa*, *Montaña Clara* and *Alegranza* there is not much to say. The two latter are comparatively recent volcanic islands with no great heights. Marine abrasion has played the greatest role, facilitated by the soft volcanic material.

CONCLUSIONS

As a summary of what has been expounded in the preceding pages we may stress the following circumstances:

The Canary islands are built of a variegated series of volcanic products with different degree of resistance to exogenic forces and gravitation. The islands rise from a relatively deep sea and have consequently

large underwater socles. The supramarine structures are lofty too in general and the coasts are mostly steep.

The archipelago lies in the zone of the northeastern trade wind bringing moisture to the windward sides and agitating the sea.

The windward sides of the islands receive water percolating into the ground, causing saturation with ground water and creating in certain cases lubricating underground surfaces adapted for slipping.

Volcanic outbursts that have affected the islands from time to time have certainly been the trigger of great avalanches made ripe through the percolation of ground water or erosion.

The lee side of the islands and especially the easternmost islands have a drier climate which provokes disintegration of the rocks, causing rock falls and creep.

Most avalanches seem to have taken place in earlier periods of somewhat different climatic conditions and a more active volcanism. The present time signifies a decrease in the intensity of the exogene gravitational adjustments, since erosion is sparse. More vigorous exogenic processes prevailed during the pluvials in Quaternary time. The present relief is consequently not the result of existing conditions but inherited from the past.

About submarine landslides or turbidity currents within the Canaries nothing is known.

In short it can be stated that among the exogenic processes in the Canaries landslides have had their great share when considering the actual relief, and these events have, it seems, had a much greater importance in the past, due chiefly to greater moisture and frequent earthshocks, since the volcanism is now known to be fading away.

As is well known, the present time is one of great advances in study of the ocean floor and its tectonical behaviour. Following the concept of sea floor spreading out from the Mid-Atlantic ridge, one has to consider the Canaries as having taken part in this spreading. Recent investigation (1968) with the aid of paleomagnetism and K / Ar dating methods have shown that at least some of the islands in this archipelago are arranged in an order of increasing antiquity in the direction west — east. This would mean that the Purpuraries, Fuerteventura and Lanzarote are the relatively oldest of the islands, La Palma and Hierro the youngest in the series. A study of the morphology of the islands, of landslides as well as river erosion and weathering in general, seems to confirm the existence of such age relations among the islands. This

may explain the very advanced maturity of the relief in the Purpuraries, compared with the conditions in the more western islands (including Gomera). The author has several years ago tried to characterize the morphologic condition of Fuerteventura (1956) as standing in sharp contrast to that of the more westerly islands.

The young volcanism that has developed on a grand scale in Lanzarote and to some extent also in Fuerteventura is an anomaly with respect to these environments, a revival after a very long period of volcanic quiescence.

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